Chapter 5

THE EXPRESSION OF GLOBAL PALAEOENVIRONMENTAL AND CLIMATIC CHANGES IN AUSTRALIA DURING THE MID-CRETACEOUS

Abstract

Biochronostratigraphy for the Tethyan and Boreal mid-Cretaceous (Barremian-Albian) is traditionally based on ammonites. Because of the lack of useful ammonites in the Australian mid-Cretaceous, and the existence of strong faunal and floral latitudinal contrasts, to date chronostratigraphic correlation between the different realms is not straightforward. In the present study dinoflagellate cyst events (first and last occurrences) combined with changes in organic-carbon-isotope ($\delta^{13}C_{org}$) stratigraphy are demonstrated to be good indicators for assessing the mid-Cretaceous Stage and Substage boundaries in Australia. The Australian dinocyst information was compared to ammonite calibrated Tethyan and Boreal successions. This resulted in recognition of global dinocyst events as well as in age assessment for Australian dinocyst zones of the traditional dinocyst zonal scheme. The established stratigraphic framework further allowed comparison of the $\delta^{13}C_{org}$ records with time equivalent isotope records from other areas. Correlation of the selected results reveals similar patterns and responses in the $\delta^{13}C_{org}$ records for the Tethyan, Boreal and Austral realms, and that two periods of oceanic anoxic events (OAE) representing OAE 1a and 1c, can be recognized in Australia as well.

In Australia the inferred relatively warm and wet conditions prior to the presumed OAE 1a change to cooler and drier conditions at the start of the event. In the marine environment this temperature shift was coeval with a maximum sea-level rise of the Ap3 sequence; possibly coinciding with the development of a circum-Antarctic-Australian connection in the Early Aptian bringing cold waters to northeastern Australia.

The Toolebuc Formation in Australia correlates to OAE 1c and palaeoenvironmental reconstructions indicate relatively cooler and drier conditions at the onset of the Toolebuc in comparison to the later part, when conditions became warmer and more humid. Within the Toolebuc a threefold division in sea-level can be made, e.g., a rise in the lower part; a fall in the middle and correlative to sequence boundary Al7; followed by a rise again in the upper part. In agreement with the climatic changes inferred for the Early Cretaceous, the succession of events in the Toolebuc Fm shows a fluctuating pattern toward increasingly warmer environmental conditions.

1. Introduction

The Cretaceous is generally accepted to represent a time of fluctuating geochemical cycling, evolution and climate, during which the warmest periods observed in Earth’s history alternated with cooler periods as well as seasonality (e.g. Frakes and Francis, 1990; Hay, 1995; Erbacher et al., 1996; Mutterlose, 1998; Premoli Silva and Sliter, 1999). The nature and contemporaneity of the changes in the Tethyan and Boreal realms have been the subject of detailed correlation programs combining bio-, chemo-, cyclo-, isotope-, and magnetostratigraphy (e.g. Hoedemaeker et al., 1993; Leereveld, 1995; Erba, 1996; Hoedemaeker, 1999). The multitude of records of the various parameters and the inferred stratigraphic events were tied to the established Tethyan and Boreal ammonite zonation schemes, for firm biostratigraphic control (Hoedemaeker et al., 1993; Hoedemaeker and Rawson, 2000).

Cretaceous chronostratigraphy is traditionally based on ammonites because they provide high resolution and best long-distance correlation. However, the first useful, Cretaceous ammonites in Australia to show affinity with European taxa were inferred to occur around the Aptian-Albian boundary (Day, 1969). This lack of precise biostratigraphical correlation and accurate geochronology (by e.g., magnetic polarity events) complicates exact placement of Australian sequences within the Cretaceous System.

In the last decade dinoflagellate cysts (dinocysts) have shown to provide a strong alternative tool to stratigraphically correlate widely separated marine sections (e.g. Prauss, 1993; Hoedemaeker and Leereveld 1995; Wilpshaar, 1995; Torricelli, 2000) and several dinocyst events (first and last occurrences) can even be traced globally (Leereveld, 1997; Oosting et al., in prep.; Chapters 2, 3, and 4). Moreover, quantitative dinocyst records register palaeoenvironmental and climatic changes, because they are sensitive to changes in the marine environment, like in sea-surface temperature, nutrient supply, salinity, and light penetration. As a consequence, in studies on fossil dinocysts, variations within the assemblages may be considered to reflect the environmental and climatic conditions at the time.

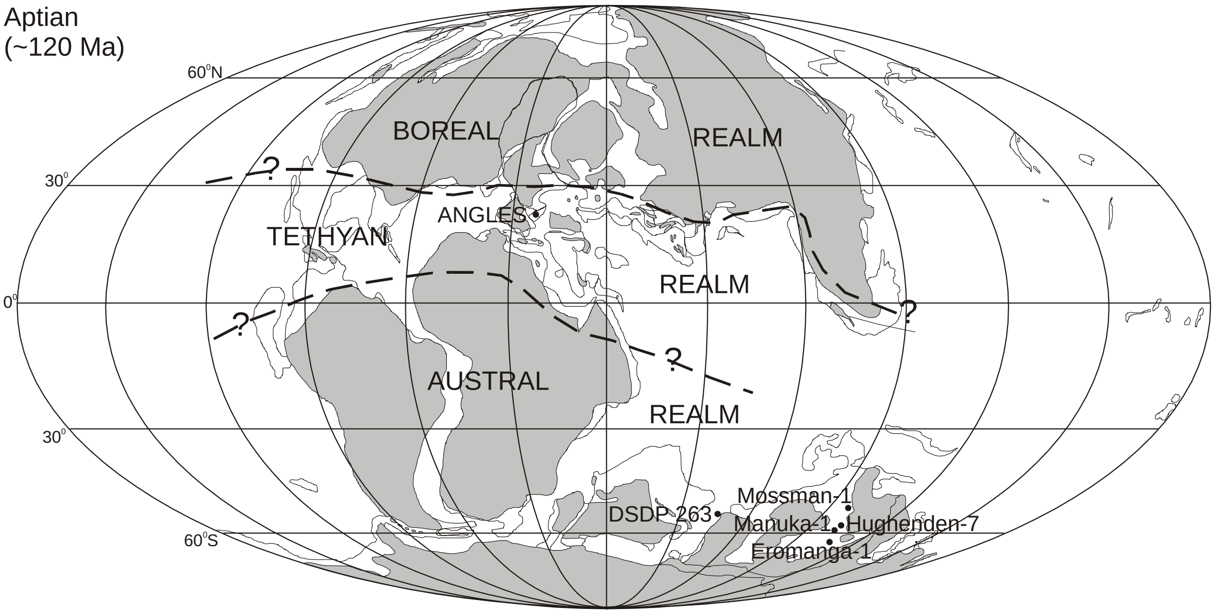

Figure 1. Map of the Early Cretaceous ca. 120 Ma showing land (shaded) and shallow seas (adapted from Hay et al., 1999) with general outline of the Boreal, Tethyan and Austral realms. Approximate locations for Angles, DSDP site 263, BMR Mossman-1, GSQ Hughenden-7, GSQ Manuka-1 and GSQ Eromanga-1.

During the periods of global warming in the mid-Cretaceous, the equator-to-pole temperature gradient decreased (Barron, 1983; Huber et al., 1995), leading to sluggish oceanic conditions and diminished deep-water formation hampering oxygenation of the water column (e.g. De Boer , 1986), causing the oxygen minimum zone to expand. These changes led to deposition of conspicuous organic-rich layers in deep marine settings, also referred to as Oceanic Anoxic Events (OAEs; Schlanger and Jenkyns, 1976; Jenkyns, 1980). These OAEs correspond to excursions in the carbon isotope (δ^{13}C) record and in the total amount of organic carbon stored (e.g. Menegatti et al., 1998; Bralower et al., 1999; Leckie et al., 2002). Several authors recognized intervals in the $\delta^{13}C_{org}$ records showing changes in a same pattern and with a comparable magnitude in sequences from different areas and defined these characteristic intervals as carbon isotope segments (e.g. Menegatti et al., 1998; Bralower et al., 1999).

In European sections, e.g., Erba et al. (1996) and Wissler et al. (2002) have shown that the events in the $\delta^{13}C_{org}$ records correspond to distinct biostratigraphic events (nannofossils and foraminifera). In the present study is explored if a similar correspondence can be inferred for dinocyst and organic-carbon-isotope stratigraphy in Australian and European sections. If so, this combination would provide a strong stratigraphic tool for the assessment of the position of mid-Cretaceous Stage and Substage boundaries in Australia. To this end is determined how Australian sections and the identified Australian dinocyst zones (according to the zonation scheme by Helby et al., 1987) fit into the global chronostratigraphic framework, and only those dinocyst events qualify which occur more or less contemporaneous in the Tethyan, Boreal and Austral sections. To test whether the dinocyst events from Australian sequences are synchronous with those from the Tethyan and Boreal realms, and their distribution not merely controlled by local palaeoenvironmental parameters, they were also correlated to the organic-carbon-isotope ($\delta^{13}C_{org}$) records for the sequences.

The selected sections from the Austral Realm come from three different Cretaceous, depositional basins and are (Figure 1): NW Shelf of Australia (Deep Sea Drilling Program (DSDP) site 263; the $\delta^{13}C_{org}$ record for this sequence is presented later in this chapter), the Carpentaria Basin (NE Australia; Bureau of Mineral Resources (BMR) Mossman-1) and the Eromanga Basin (central Australia; Geological Survey of Queensland (GSQ) Hughenden-7, GSQ Manuka-1 and GSQ Eromanga-1). These were then correlated to the ammonite calibrated, Barremian type section at Angles (SE France). Followed by further comparisons with $\delta^{13}C_{org}$ records from Tethyan and Boreal mid-Cretacoeus sequences, which is available from a multitude of studies (e.g. Menegatti et al., 1998; Bralower et al., 1999; Hochuli et al., 1999; Jenkyns and Wilson, 1999; Jahren et al., 2001; Wissler et al., 2002; De Gea et al., 2003).

The correlation between the dinocyst and organic-carbon-isotope stratigraphy from Australian and European sections enables correlation of the depositional cycles recognized in the Australian sections with the Barremian to Albian part of the global sea-level variations propagated by Hardenbol et al. (1998) and the sequence stratigraphic framework by Jacquin et al. (1998). Furthermore, the carbon-isotope segments inferred for Europe (e.g. Menegatti et al., 1998; Bralower et al., 1999) and recognized in Australia, together with the inferred palaeoenvironmental and climatic changes, allow identification of two OAE events (e.g., OAE 1a and 1c) in Australia, clearly indicating that these events were of global extent.

2. Stratigraphic framework

Dinocysts

The collective dinocyst events from the sites selected for this study were correlated to the ammonite calibrated Tethyan and Boreal events as inferred by Leereveld (1995; 1997a, b). In those studies he compiled ammonite controlled dinostratigraphic data from Tethyan and Boreal sections and directly correlated these to standard chronostratigraphy (Hoedemaeker et al., 1993; Hoedemaeker and Leereveld, 1995). Although since then slightly modified versions of ammonite zonation schemes were published (Hoedemaeker, 1999; Hoedemaeker and Rawson, 2000), the positions of the dinocyst events were not affected.

For the Austral Realm, more than a decade ago a comprehensive dinoflagellate zonation was established for stratigraphic correlation of a wide variety of Jurassic-Cretaceous marine sections (Helby et al., 1987). Although, this zonal scheme is adapted to the needs of various workers, the resultant providing a solid tool for pan-Australian biostratigraphic correlations, its details are mostly unpublished (Foster, 2001). This lack of reference to other biostratigraphic zonations, such as provided by ammonites taken as the global standard (Gradstein et al., 1998) and other chronostratigraphic methods such as magnetic polarity events, hampers the scheme.

In the present study a stratigraphic framework is established based on dinocyst events, which occur more or less contemporaneous in the Tethyan, Boreal and Austral sections (see Chapters 2, 3, and 4). In addition to the correlation of these inferred global events (Figure 2) is here focused on recognition of the Australian dinocyst zones by Helby et al. (1987; Figure 3). Those stratigraphically diagnostic dinocyst events considered important in Australian correlations (see Chapters 2 to 4) but not included in the zonation scheme are discussed in the present study as well.

The taxonomy and nomenclature of dinocysts follows the Lentin and Williams Index (Williams et al., 1998) unless otherwise stated.

Organic-carbon-isotopes

For direct comparison of Australian $\delta^{13}C_{org}$ records with the global $\delta^{13}C_{org}$ signature the terminology of Menegatti et al. (1998) and Bralower et al. (1999) was used (see Chapters 3 and 4). Menegatti et al. (1998) published carbonate and organic-carbon-isotope records for the latest Barremian to Early Aptian (including OAE 1a) from the Tethyan Cismon and Roter Sattel sections. Based on characteristics in the $\delta^{13}C_{org}$ curve Menegatti et al. (1998) divided the isotope record into eight C-segments (e.g. C1 to C8) with the Aptian boundary within isotope segment C2; in accordance with Erba (1996) the base of polarity Chron M0 was considered the base of the Aptian.

Erba et al. (1999) published a higher-resolution carbon (C_{carb}) isotope record for the Upper Hauterivian-Lower Aptian of the Cismon section, in which particularly the nature of segment C2 seemed to be modified, i.e. instead of showing decreasing C_{carb} values toward the top of this segment as in Menegatti et al. (1998), it shows increasing values (Erba et al., 1999).

Bralower et al. (1999) further determined the global extent of the C-segments by correlating Atlantic sequences to the Cismon section. They used the same terminology as Menegatti et al. (1998) and further extended it with segment C9 to C15, into the Albian (see also Chapter 3). Here we use the segments identified by Menegatti et al. (1998) and Bralower et al. (1999), but for segment C2 the revised version of Erba et al. (1999) is applied.

3. Dinostratigraphy

In this paragraph the dinocyst events determined in the studied sections (being: Angles and DSDP site 263 in Chapter 2, BMR Mossman-1 in Chapter 3, GSQ Hughenden-7, GSQ Manuka-1 and GSQ Eromanga-1 in Chapter 4) are compiled with evaluation of their potential global application. Below the relevant taxa are listed alphabetically and the events (FO = first occurrence, LO = last occurrence) are indicated for the Austral, Tethyan and Boreal realms in Figure 2.

3.1 *Evaluation of global dinocyst events*

Carpodinium granulatum

The FO of this species lies in the Boreal *germanica* belemnite Zone (compare with e.g., Heilmann-Clausen and Thomson, 1995), and to the Boreal *pingue*/*innexum* ammonite Chronozone (middle Upper Barremian; Mutterlose, 1992). To date this species has not been reported from the Tethyan Realm.

In Boreal records by Heilmann-Clausen and Thomson (1995) the occurrence of *C. granulatum* in the Barremian is rare and it only appears consistently in the earliest Aptian. In this study the FO in DSDP site 263 is reported from the Upper Barremian while in BMR Mossman-1, GSQ Manuka-1 and Eromanga-1 it was documented from the earliest Aptian; the stratigraphic positions correlate to the Austral *M. australis* Zone of Helby et al. (1987). The FO in the Austral Realm is probably related with an influx of cooler waters during the rapidest phase of the earliest Aptian transgression (Hardenbol et al., 1998; Jacquin et al., 1998), corresponding to the global carbon isotope segments C4 to C6 (Menegatti et al., 1998; see Chapter 3).

Kleithriasphaeridium fasciatum

The LO of this species is documented from the middle *vandenheckii* ammonite Chronozone (lowermost Upper Barremian) it concerns records of De Renéville and Raynaud (1981) in the Angles section (SE France) and Leereveld (1995) in Spain. Based on Wiseman & Williams (1974) in DSDP site 263 (offshore NW Australia) the event correlates to the Austral *Muderongia testudinaria* Zone of Helby et al. (1987).

Litosphaerium arundum

The FO of this species is documented from the lowermost Tethyan *tardefurcata* and the upper Boreal *tardefurcata* ammonite Chronozones (earliest Albian; Davey and Verdier, 1971). According to Leereveld (1995) and Hart et al. (1996) the inception correlates to the Aptian-Albian boundary. In the present study the FO was found in GSQ Hughenden-7, GSQ Manuka-1 and GSQ Eromanga-1.; the particular stratigraphic positions correlate to the base of the Australian *M. tetracantha* Zone (Helby et al., 1987).

Muderongia staurota

In the Angles section (SE France, Chapter 2) the LO of this species is recorded from the middle of the Tethyan *sarasini* ammonite Chronozone (latest Barremian). This biostratigraphic position agrees with its LO in the Spanish Río Argos section (Leereveld, 1997). In NW Germany (Prössl, 1990) and in E England (Leereveld, unpublished) its LO is in an interval corresponding to the middle of the *Oxytheuthis germanica* belemnite Zone (middle Upper Barremian). In the Austral Realm the stratigraphic range of the broad variety of *Muderongia* species reaches younger stratigraphic intevals (i.e., into the *Muderongia australis* Zone: Helby et al. (1987) and DSDP site 263 in Chapter 2) than in Europe, i.e. Aptian rather than latest Barremian.

Odontochitina operculata

The FO of this species in the Angles section was documented by Wilpshaar (1995) from the lower *vandenheckii* ammonite Chronozone (lowermost Upper Barremian). According to Duxbury (1980) its inception in the Boreal Realm correlates to the *elegans* ammonite Chronozone (basal Upper Barremian). According to Helby et al. (1987) the FO of *O. operculata* in the Austral Realm can be observed coeval with the regional dinocyst events: FO of *Heerendenia postprojecta*, FO of *Ovoidinium cinctum* and FO of *Dapsilidinium ambiguum*. However, in the present study in DSDP 263, the FO of *O. operculata* is considerably later than of *H. postprojecta* and *D. ambiguum* but these latter two occur prior to the global dinocyst events: LO of *P. neocomica*, FO of *C. granulatum* and FO of *T. sousensis* (all events reported from the Upper Barremian; see above; Chapter 2), and after the FO of *P. parvispinum* (Upper Barremian; see above; Chapter 2). This would imply that the FO of *O. operculata* in the Austral Realm lies within the Upper Barremian.

Phoberocysta neocomica

The LO of this species is reported from the upper *tuarkyricus* ammonite Chronozone in Angles (lowermost Aptian; Chapter 2); this position is confirmed by the record of its LO in N Italy (lower part of magnetic polarity chron M0: Torricelli, 2000). In the European Boreal it is documented from the Lower Aptian *forbesi* ammonite Zone (Isle of Wight: Duxbury, 1983). In Australia the stratigraphic top of *Phoberocysta neocomica* is recorded from the middle *M. australis* Zone (Helby et al., 1987; DSDP site 263: Wiseman and Wiliams, 1974), an interval correlative to the Upper Barremian.

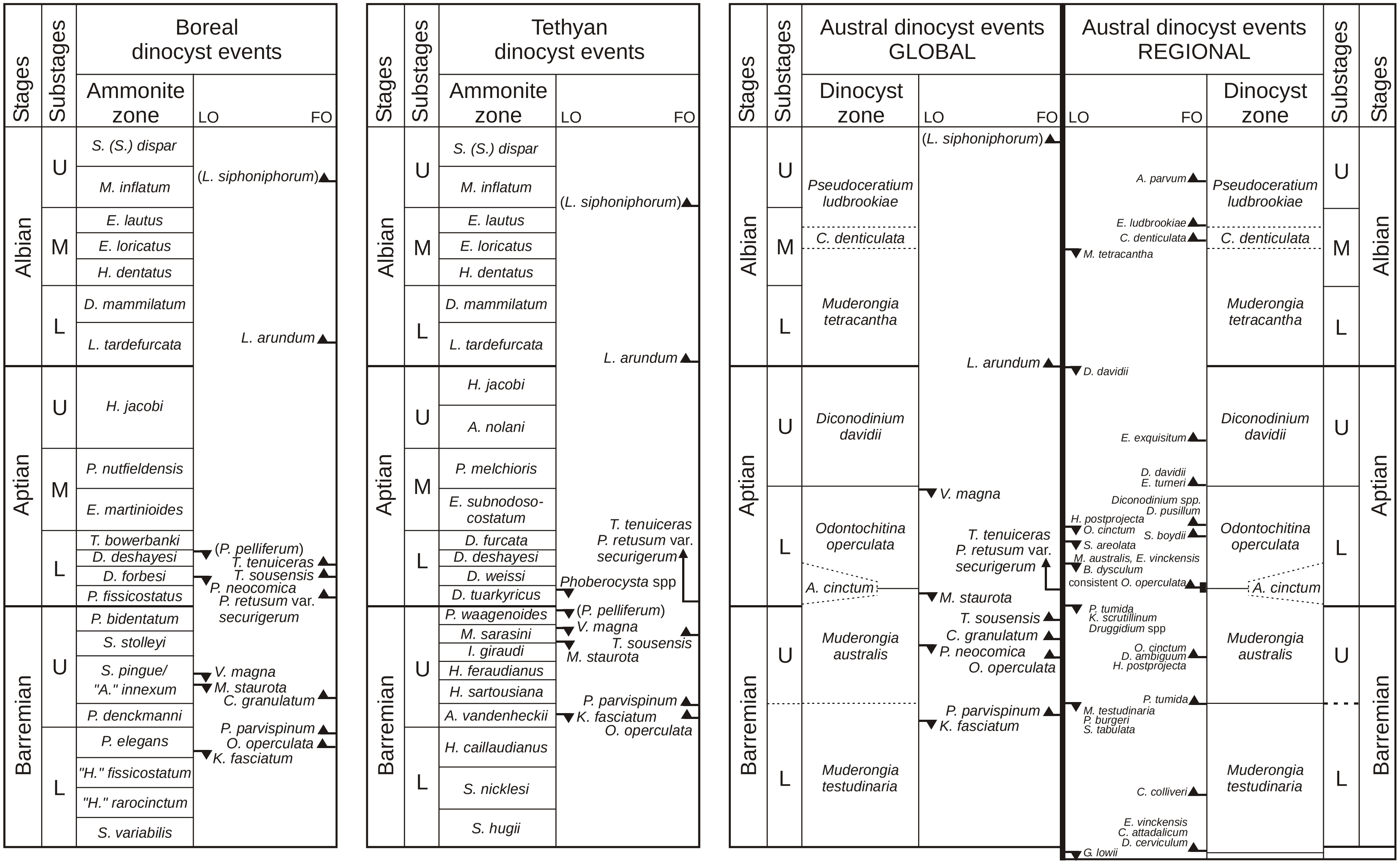

Figure 2. The Boreal and Tethyan ammonite calibrated dinocyst events (adapted from Leereveld, 1995) correlated to global dinocyst events occurring in Australia and events of regional importance according to the Helby et al. (1987) zonation scheme. ▼ = LO (Last Occurrence), ▲ = LO (First Occurrence)

Prolixosphaeridium parvispinum
The FO of this species was documented from the middle *vandenheckii* ammonite Chronozone in Angles (lowermost Upper Barremian) by De Renéville and Raynaud (1981), which position is confirmed by the FO reported from Italy (near the base of magnetic chron M1: Torricelli, 2000). Based on Wiseman & Williams (1974) in DSDP site 263 (offshore NW Australia) the event correlates to the Austral *M. testudinaria* Zone of Helby et al. (1987). In the present study the FO is documented from BMR Mossman-1, GSQ Hughenden-7, GSQ Manuka-1 and GSQ Eromanga-1.

Pseudoceratium retusum var. *securigerum*
The FO of this species was documented from the Boreal *fissicostatus* ammonite Chronozone (Lower Barremian) by Duxbury (1983). According to Davey & Verdier (1974) and Masure (in Rasplus et al., 1987) it consistently appears, in Tethyan ammonite controlled sections, in the lowermost Aptian. In the present study the FO was found in Angles and DSDP site 263; the stratigraphic position correlates to the *M. australis* Zone.
Typical European Barremian-Aptian *Pseudoceratium* such as *P. pelliferum* and *P. retusum* (including *P. retusum* var. *anaphrissum* and *P. retusum* var. *securigerum* of Leereveld, 1997) are virtually absent from Australian dinoflagellate assemblages but when *P. retusum* var. *securigerum* is present it enables a more precise assignment of the Barremian-Aptian boundary (Oosting et al., in prep; Chapter 2).

Tehamadinium sousensis
The FO of this species is reported from the middle of the Tethyan *sarasini* ammonite Chronozone (latest Barremian; Oosting et al., in prep.; Chapter 2). In borehole sections from NW Germany its appearance is associated with the extinction of *Phoberocysta neocomica*, i.e. corresponding to the *forbesi* ammonite Chronozone (Lister & Batten, 1995; Heilmann Clausen & Thomsen, 1995). In the present study its FO was found in Angles, DSDP site 263 and BMR Mossman-1; the stratigraphic position correlates to the Austral *M. australis* Zone of Helby et al. (1987).

Tehamadinium tenuiceras
In the Tethyan Realm, the FO of the species lies in the *tuarkyricus* ammonite Chronozone (earliest Aptian, Leereveld, 1995). In the Boreal Realm it lies in the *deshayesi* ammonite Chronozone (middle Lower Aptian; Duxbury, 1983). In the present study it was found in Angles, DSDP site 263, BMR Mossman-1 and GSQ Eromanga-1; the event in Australia correlating to the uppermost *M. australis* Zone of Helby et al. (1987). The FO of this species is consistently reported from Australian sections and seems a reliable indicator for the earliest Aptian (Oosting et al., in prep.; Chapter 2).

Valensiella magna
The LO of this species in the Angles section is reported from the uppermost *sarasini* ammonite Chronozone (uppermost Barremian; Oosting et al., in prep.; Chapter 2). In the Boreal Realm its LO is in an interval corresponding to the middle of the *O. germanica* belemnite Zone (middle Upper Barremian; Prössl, 1990; H. Leereveld, unpublished). In the Austral Realm the stratigraphic range of the broad variety of *Valensiella* species reaches younger stratigraphic intevals (i.e., into the *O. operculata* Zone: Helby et al. (1987) and DSDP site 263, BMR Mossman-1 and GSQ Eromanga-1) than in Europe, i.e. Lower Aptian rather than Upper Barremian.

3.2 *Evaluation of Austral dinocyst events*

For an evaluation of the dinoflagellate distribution patterns in the studied intervals from DSDP site 263, BMR Mossman-1, GSQ Hughenden-7, GSQ Manuka-1 and GSQ Eromanga-1, in terms of

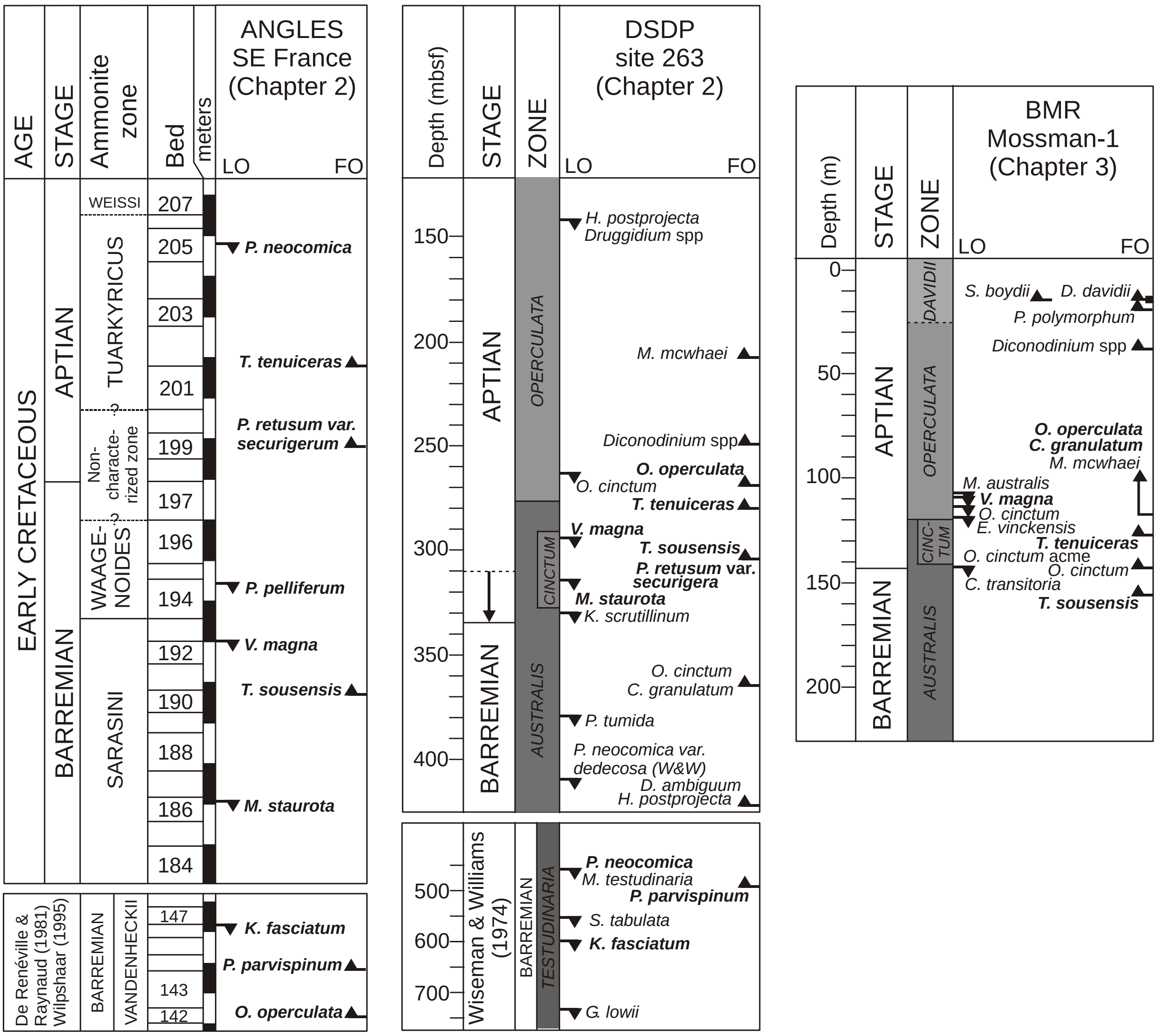

Figure 3. The selected global and regional dinocyst events for Angles, DSDP site 263, BMR Mossman-1, GSQ Hughenden-7, GSQ Manuka-1 and GSQ Eromanga-1. Australian dinocyst zones are according to the Helby et al. (1987) zonation scheme. LO = Last Occurrence, FO = First Occurrence.

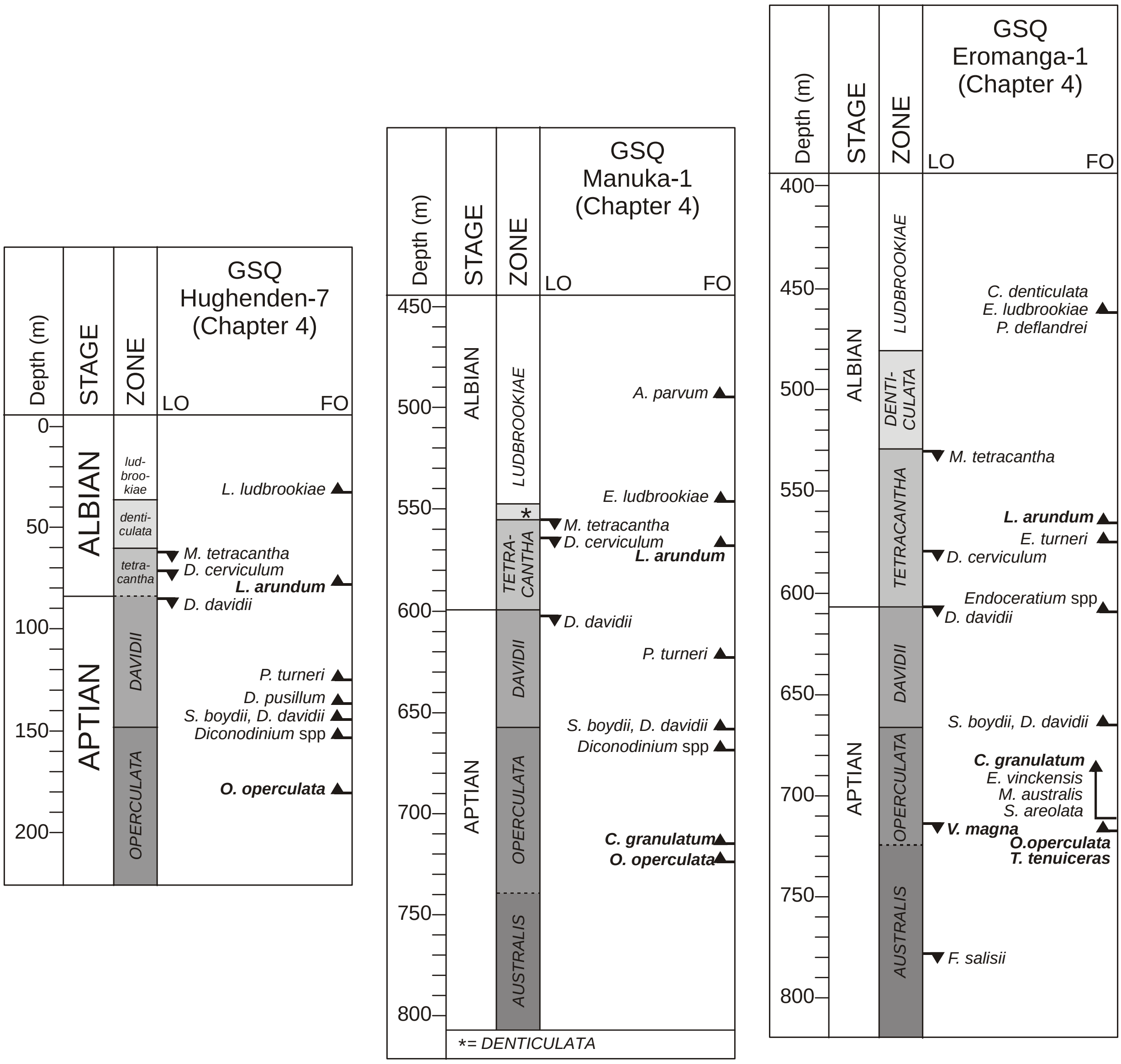

Figure 3 (continued).

the Australian Barremian to Albian, mainly qualitative, diagnostic dinocysts events are considered relevant for recognition of the Helby et al. (1987) zones (Figure 3).

Angustodinium acribes
This taxon shows a minor acme within the *O. operculata* Zone in DSDP site 263 and BMR Mossman-1.

Ascodinium parvum
The FO of this species (middle *E. ludrookiae* Zone; Helby et al., 1987) was observed in GSQ Eromanga-1.

Canninginopsis denticulata
Its FO (middle *C. denticulata* Zone; Helby et al., 1987) was observed in GSQ Hughenden-7, GSQ Manuka-1 and GSQ Eromanga-1.

Canningia transitoria
The LO of this species within the *M. australis* Zone was reported from the Houtman-1 Well by Stover and Helby (1987b) and shows a similar range in BMR Mossman-1 from the Carpentaria Basin.

Diconodiniium davidii
The LO of *D. davidii* defines the top of the *D. davidii* Zone and the base of the succeeding *Muderongia tetracantha* Zone (Helby et al., 1987). An acme in *D. davidii* is characteristic of the

D. davidii Zone. The FO and acme of this species were observed in BMR Mossman-1, GSQ Hughenden-7, GSQ Manuka-1 and GSQ Eromanga-1.

Diconodinium pusillum
Its FO (middle *O. operculata* Zone; Helby et al., 1987) was observed in BMR Mossman-1, GSQ Hughenden-7, GSQ Manuka-1 and GSQ Eromanga-1.

Diconodinium spp
Representatives of the genus typically appear in the middle *O. operculata* Zone (Helby et al., 1987). It the present study it was observed in DSDP site 263, BMR Mossman-1, GSQ Hughenden-7, GSQ Manuka-1 and GSQ Eromanga-1.

Dingodinium cerviculum
The LO of *D. cerviculum* (middle *M. tetracantha* Zone; Helby et al., 1987 was observed in GSQ Hughenden-7, GSQ Manuka-1 and GSQ Eromanga-1.

Endoceratium ludbrookiae
The FO of *E. ludbrookiae* marks the top of the *C. denticulata* Zone and the base of the *Endoceratium ludbrookiae* Zone (Helby et al., 1987). The FO of this species was observed in GSQ Hughenden-7, GSQ Manuka-1 and GSQ Eromanga-1.

Endoceratium polymorphum
Its FO (uppermost *O. operculata* Zone; Helby et al., 1987) was observed in BMR Mossman-1.

Endoceratium turneri
According to Helby et al. (1987) the FO of *E. turneri* marks the base of the *D. davidii* Zone and its inception is considered to be coeval with that of *E. turneri* (Helby et al., 1987, figure 26).

However, Morgan (1980a) postulated that in the Great Artesian Basin *D. davidii* may occur prior to *E. turneri*. This latter relationship was also observed in the present study i.e., in GSQ Hughenden-7, GSQ Manuka-1 and GSQ Eromanga-1.

Epitricysta vinckensis
The LO of *E. vinckensis* (lower *O. operculata* Zone, Helby et al., 1987) was observed in DSDP site 263, BMR Mossman-1 and GSQ Eromanga-1.

Herendeenia postprojecta.
This species consistently appears in the middle of the *M. australis* Zone and the extinction of the species is characteristic of the middle *O. operculata* Zone. Its FO was observed in DSDP site 263.

Kaiwaridinium scrutillinum
The extinction of the species lies in the upper *M. australis* Zone (Helby et al., 1987) and prior to the *O. cinctum* Zone, when the latter can be inferred. Its LO occurs in DSDP site 263.

Muderongia australis
The LO of this species (lowermost *O. operculata* Zone, Helby et al., 1987) was observed in BMR Mossman-1 and GSQ Eromanga-1.

Muderongia mcwhaei
In alternative correlations (e.g. in the Carnarvon Basin; Helby et al., 1987) the FO of this species defines the base of the *O. operculata* Zone, instead of the FO of *O. operculata*. The FO of *M. mcwhaei* was observed in DSDP site 263, BMR Mossman-1, GSQ Manuka-1 and GSQ Eromanga-1.

Muderongia testudinaria
The LO of this species was reported by Wiseman and Williams (1974) from DSDP site 263 (base *M. australis* Zone, Helby et al., 1987).

Muderongia tetracantha
The LO of *M. tetracantha* marks the top of the *M. tetracantha* Zone and the base of the succeeding *Canninginopsis denticulata* Zone (Helby et al., 1987). Its LO was observed in GSQ Hughenden-7, GSQ Manuka-1 and GSQ Eromanga-1.

Ovoidinium cinctum
An acme in *O. cinctum* defines the *O. cinctum* Zone (Helby et al., 1987). In the present study this zone is only truly developed in BMR Mossman-1 (Chapter 3), and it is possibly contained in DSDP site 263 (Oosting et al., in prep.; Chapter 2). Because of it facies depence and irregular distribution pattern in Australia, in this study is chosen to incorporate the *O. cinctum* Zone within the upper part of the preceding *M. australis* Zone (see Figure 5).
In the Boreal Realm, Lister and Batten (1988) reported *O. cinctum* to appear in the *bowerbanki* and *martinioides* ammonite Chronozones (Early Aptian). In the Austral Realm, Helby et al. (1987; and also in Foster, 2001) suggested the Barremian-Aptian boundary to fall within the *O. cinctum* Zone. This implies that the acme zone would correlate to the standard uppermost Barremian *waagenoides* and basal Aptian *tuarkyricus* ammonite Chronozones. However, direct biostratigraphic correlation of the data from the present study with ammonite controlled sections shows that the acme zone correlates with the Early Aptian *tuarkyricus* and lower *weissi* ammonite Chronozones (Oosting et al., in prep.; Chapter 3; Figure 5), inferring a slightly younger age for the zone than postulated by Helby et al. (1987) and Foster (2001). The Barremian-Aptian boundary consequently falls within the top of the preceding *M. australis* Zone.

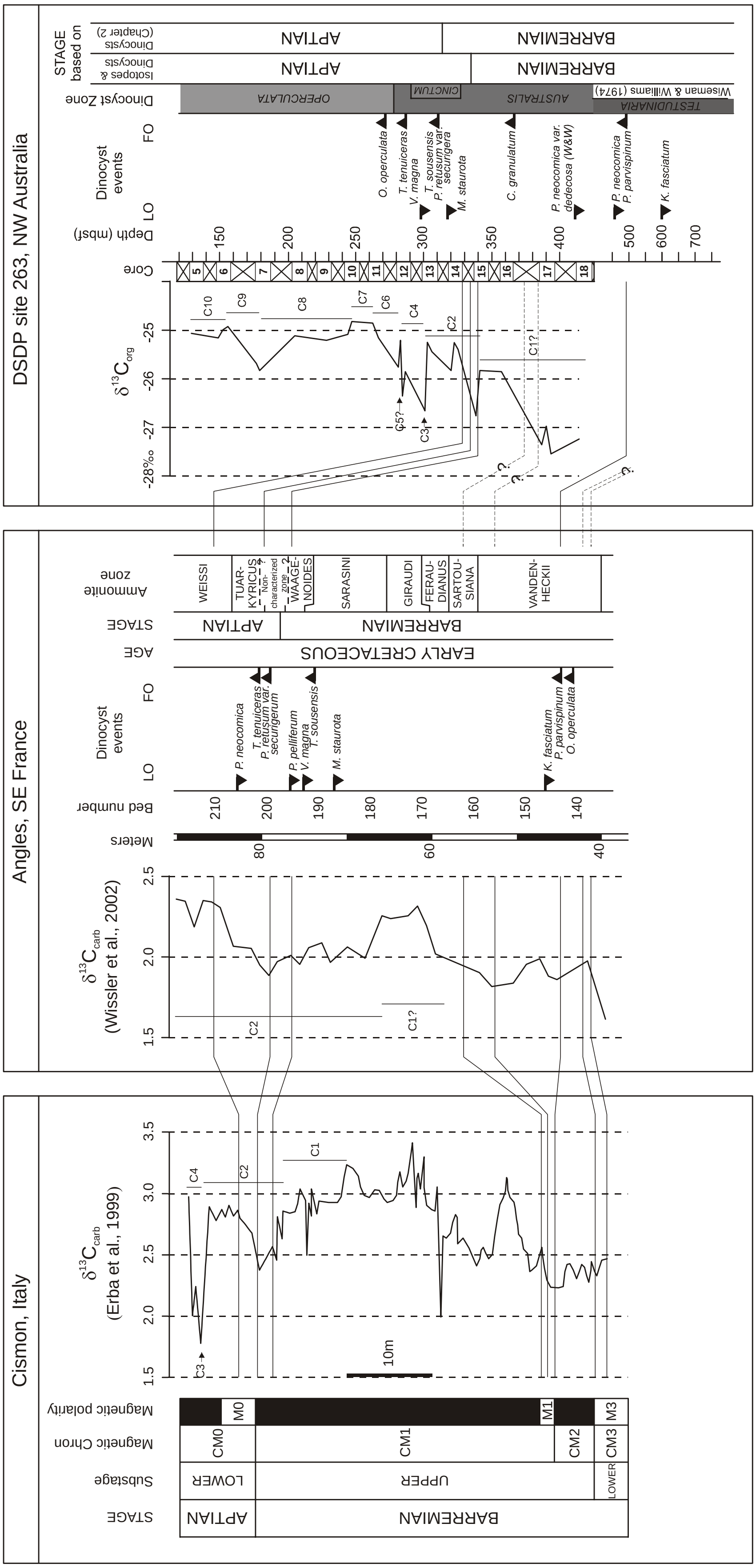

Figure 4. Correlation of δ13Corg records from the Cismon section (Italy; Menegatti et al., 1998; Erba et al., 1999), Angles (France, Wissler et al., 2002) and DSDP site 263. Labels C1 to C10 represent segments of the δ13Corg curves and are discussed in the text.

Palaeoperidinium cretaceum
According to Harding (1990) this species occurs in environments with less than normal marine salinity. Its abundance shows a minor acme in BMR Mossman-1 and GSQ Eromanga-1, in the lower *O. operculata* Zone (Helby et al., 1987).

Phoberocysta neocomica var. *dedecosa*
The LO of this species (middle *M. australis* Zone, Helby et al., 1987) was documented by Wiseman &Williams (1974) from DSDP site 263.

Pyxidiella tumida
The species is restricted to the *M. australis* Zone (Helby et al., 1987) and its LO was observed in DSDP site 263.

Spinidinium boydii
The FO of this species (lower *O. operculata* Zone, Helby et al., 1987) was observed in BMR Mossman-1, GSQ Hughenden-7, GSQ Manuka-1 and GSQ Eromanga-1.

Systematophora areolata
The LO of *S. areolata* (middle *O. operculata* Zone, Helby et al., 1987) was found in GSQ Eromanga-1.

4. Organic-carbon-isotope stratigraphy

The Barremian to Albian biostratigraphic age assessment for the sections collectively enabled recognition of the global isotope segments C1 to C15 (as defined by Menegatti et al., 1998, and Bralower et al., 1999) in BMR Mosmann-1, GSQ Hughenden-7, GSQ Manuka-1 and GSQ Eromanga-1.
The $\delta^{13}C_{org}$ data for DSDP site 263 became available after submission of the paper on the dinocyst events from Angles and DSDP site 263 (Oosting et al., in prep.; Chapter 2). The isotope analysis was carried out at Utrecht University according to the same methods as for BMR Mossman-1 (see Chapter 3). Also, Wissler et al. (2002) recorded the Barremian to earliest Aptian $\delta^{13}C_{carb}$ record for Angles and correlated these to the Cismon $\delta^{13}C_{carb}$ record of Erba et al. (1999; Figure 4), since the interval at Angles extends below the interval studied by Menegatti et al. (1998). In the ammonite calibrated Angles section Wissler et al. (2002) observed similar $\delta^{13}C_{carb}$ patterns as in Cismon. Comparing these records reveals that isotope segment C2 comprises the *sarasini*, *waagenoides*, *tuarkyricus* and part of the *weissi* ammonite zones (Figure 4). Although Wissler et al. (2002) inferred part of the *giraudi* zone to be missing at Angles, isotope segment C1 would correlate to the upper part of this zone in Menegatti et al. (1998) and Erba et al. (1999; Figure 4).
To enable correlation between DSDP site 263 with the records from Angles and the other sequences, the $\delta^{13}C_{org}$ data for the site will be presented here first.

4.1 *The $\delta^{13}C_{org}$ record for DSDP site 263*

Given the dinostratigraphic correlation for DSDP site 263 (Oosting et al., in prep.; Chapter 2) the $\delta^{13}C_{org}$ curve compares well with the events recorded in other Barremian-Aptian, carbon-isotope records (Menegatti et al., 1998; Bralower et al., 1999; Erba et al., 1999; Wissler et al., 2002). The lowest global carbon-isotope segment inferred for DSDP site 263 is C1 and the highest is C10, as is shown in Figure 4. The Upper Barremian interval C1, characterized by increasing values, is recognized in the lower part of DSDP core 15 and cores 16 to 18. Isotope segment C2 with relative high $\delta^{13}C_{org}$ values correlates to cores 13 to upper 15 and includes the Barremian-Aptian boundary interval. Segment C3 follows C2 with a sharp negative excursion in $\delta^{13}C_{org}$ values and is inferred to correspond with the top of core 13. The successive return to more positive values over core interval 11 to 12 possibly represents segments C4-C6. The Aptian maximum during C7 would then correlate to core 10 and the upper part of core 11. In turn followed by gradually decreasing values of segment C8, a pattern possibly contained in cores 7 to 10. The sudden return to more positive values of segment C9 correlates to cores 6 and 7, followed by relative constant values of C10 over core interval 5 and 6.

Based on the FO of the dinocysts *P. retusum* var. *securigerum* and *T. tenuiceras*, marker species for the earliest Aptian (Leereveld, 1995; Erba et al., 1996; Oosting et al., in prep.; Chapter 2), the Barremian-Aptian boundary in DSDP site 263 was put between cores 12 and 13. However, the dinocyst data in combination with the $\delta^{13}C_{org}$ record, with the Stage boundary just prior to the maximum of isotope segment C2 as in Cismon (Menegatti et al., 1998), implies that the boundary at DSDP site 263 should be put slightly lower, i.e. between cores 13 and 14 (Figure 4).

4.2. *Integrated chemostratigraphy, biostratigraphy, eustacy interpretation and global $\delta^{13}C_{org}$ signature*

The integration of all biostratigraphic events observed in this study, combined with the inferred sequence stratigraphic signature from chapters 3 (Chapter 3, Figure 8) and 4 (Chapter 4, Figure 11), allowed age assignment for the global isotope segments C1 to C15 (as defined by Menegatti et al., 1998, and Bralower et al., 1999). The recognized isotope segments, with the corresponding ammonite Chronozones (according to Hoedemaeker and Rawson, 2000), the deduced dinocyst zone, and the inferred sequence boundaries (according to the terminology of Jacquin et al., 1998), are treated in ascending order and the resulting correlation is illustrated in Figure 5. Since no C-isotope segments have been inferred for the Boreal Realm to date, only the Tethyan and Austral correlatives will be treated here.

Segment C1

The base lies in the Tethyan *vandenheckii* ammonite zone (lowermost Upper Barremian) and it extends to the top of the *sarasini* zone. Within this interval sequence boundaries Ba6 (of cycle R12d of Jacquin et al., 1998) is possibly contained.
Related global dinocyst events: FO of *P. parvispinum*, LO of *K. fasciatum*, FO of *O. operculata*; and in the Austral Realm also: the LO of *P. neocomica* and FO of *C. granulatum*.
It comprises the uppermost part of the Australian *M. testudinaria*, and the major part of the *M. australis* dinocyst zones and in the Austral Realm it contains the FOs of *H. postprojecta*, *D. ambiguum* and FO of *O. cinctum*.

Segment C2

Spans from the top of the Tethyan *sarasini* to the lower *weissi* ammonite zones, as such crossing the Barremian-Aptian boundary. Includes sequence boundaries Ap1 and Ap2 (cycle R12d of Jacquin et al., 1998).
Associated global dinocyst events: FO of *T. sousensis*, LO of *M. staurota*, FO of *P. retusum* var. *securigerum*, and FO of *T. tenuiceras.*
Australian zones: upper *M. australis*, and when recognisable the lower part of the *O. cintum* Zone.
In the Austral Realm the LO of *M. staurota* and LO of *Kaiwaradinium scrutillinum* may occur within this segment.

Segment C3
In sections where this segment is contained it falls within the Tethyan *weissi* ammonite Zone (middle Lower Aptian) and marks profound changes in the palynological, geochemical and sedimentological records. The close relation of this segment with the major sequence boundary Ap3 (transition between R12d/T13 of Jacquin et al., 1998), marking a sharp 3rd order sea-level fall (see Hardenbol et al., 1998), makes that it is often not preserved in marginal marine settings.
In Australia it lies within the uppermost *M. australis*, or when differentiated, the uppermost *O. cintum* Zone (Chapter 3).

Segment C4
Lies within the Tethyan *weissi* ammonite Zone (middle Lower Aptian) and within cycle T13 of Jacquin et al. (1998).
Corresponds to an interval containing the Australian *M. australis*-*O. operculata* dinocyst zonal boundary. Within the Austral Realm it may contain the FO of *M. mcwhaei* and/or the consistent occurrence of *O. operculata*, and the base of this segment may correspond with a high influx of dinocysts associated with cool-temperate waters.

Segment C5
Correlates to the Tethyan, middle *weissi* (middle Lower Aptian) ammonite Zone and represents the transgressive surface of cycle T13 (Jacquin et al., 1998).
Correlates to the Australian uppermost *M. australis* or the lowermost *O. operculata* Zone.

Segment C6
Lies within the Tethyan *weissi* ammonite Zone (middle Lower Aptian).
It correlates to the lower Australian *O. operculata* Zone. For this segment no further diagnostic events were observed.

Segment C7
Comprises the Tethyan, upper *weissi* and lower half of the *deshayesi* ammonite zones (Lower Aptian).
It correlates to the Australian *O. operculata* Zone and the LOs of *M. australis*, *E. vinckensis* and *S. areolata* may occur.

Segment C8
Spans from the upper *deshayesi* to the middle *subnodosocostatum* ammonite Zone. The base of the latter zone defines the Lower-Middle Aptian boundary, which also corresponds with sequence boundary Ap4 of cycle R13 (Jacquin et al., 1998).
It correlates to the Australian upper *O. operculata* and lower *D. davidii* zones and may show the FOs of *S. boydii*, *Diconodinium* spp and/or *D. davidii*.

Segment C9
This segment falls within the Tethyan *subnodosocostatum* ammonite Zone (Middle Aptian) but its extent varies considerably in the different sections (see Chapter 3 Figures 8 and Chapter 4 Figure 11). The sequence boundary Ap5 of Jacquin et al. (1998) corresponds with the top of this segment.
It falls within the Australian *D. davidii* Zone.

Segment C10
It extends from the Tethyan, upper Subnodosocostatum to the *mammilatum* ammonite Zone and as such contains the Aptian-Albian boundary, which is approximated by sequence boundary Ap6, marking the transition between cycle R13 and T14 (Jacquin et al., 1998). The top of this segment also comprises Al1, Al2, and Al3. In Tethys this interval is represented by condensed section

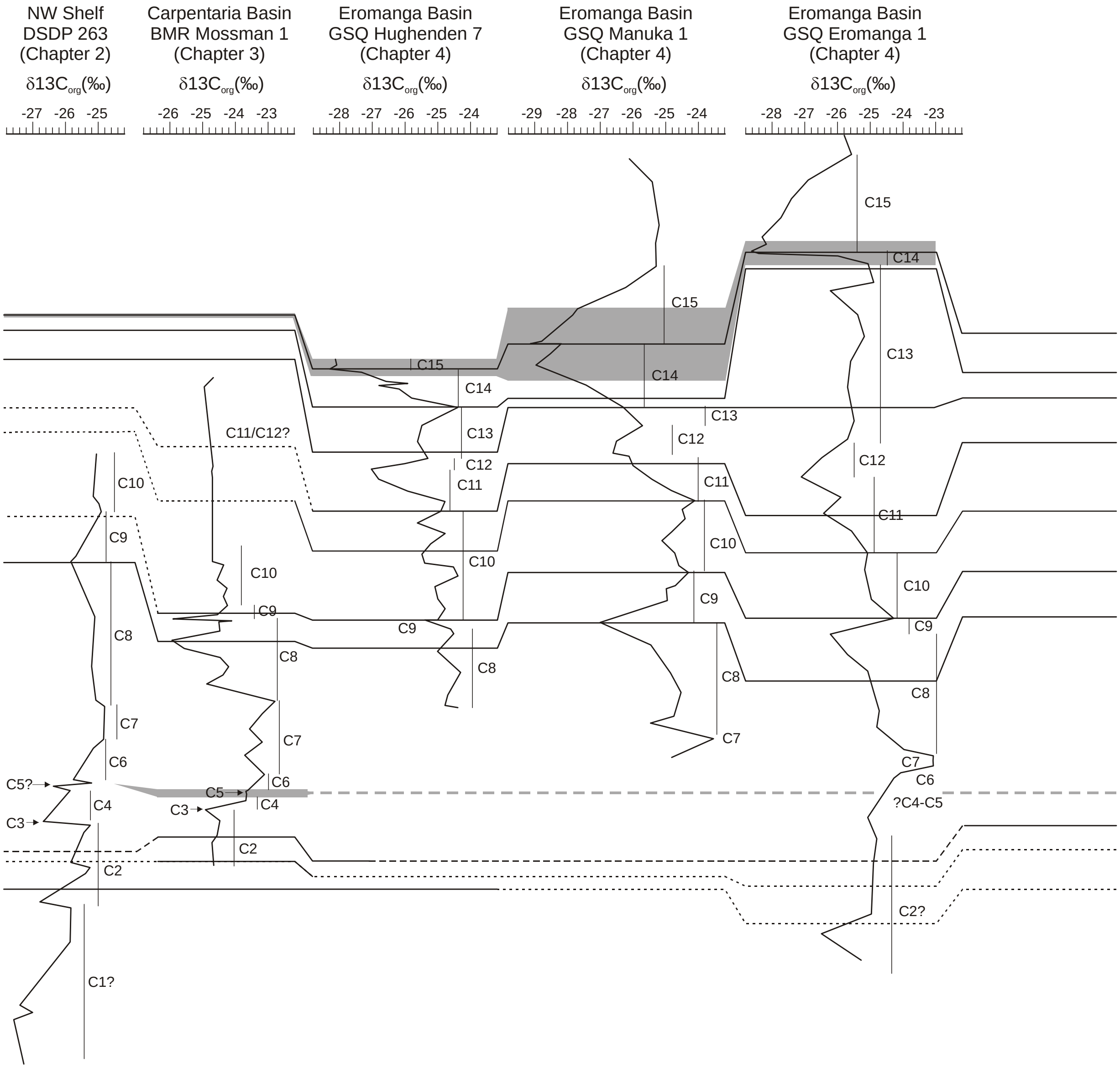

Figure 5. Correlation for DSDP site 263, BMR Mossman-1, GSQ Hughenden-7, GSQ Manuka-1 and GSQ Eromanga-1 of: isotope signature, sea-level reconstructions (based on Hardenbol et al., 1998, and Jacquin et al., 1998) with correlating Tethyan ammonite zones (Hoedemaeker and Rawson, 2000), global dinocyst events tied to the Australian Mesozoic dinocyst zonation scheme (Heby et al., 1987).

(Jacquin et al., 1998) and differentiating the sequence boundaries is in general not possible.
The segment is contained within the Australian *D. davidii* Zone, which eponymous species has its LO at the top of the segment.

Segment C11

It corresponds to the Tethyan *mammillatum* ammonite Zone (Lower Albian) and the upper part of this segment contains sequence boundary Al4 of Jacquin et al. (1998).
While the lowest Albian sequences Al1, Al2 and/or Al3 lie in the top of segment C10, the FO of *L. arundum* in the Australian sections occurs at the base of segment C11 coinciding with the base of

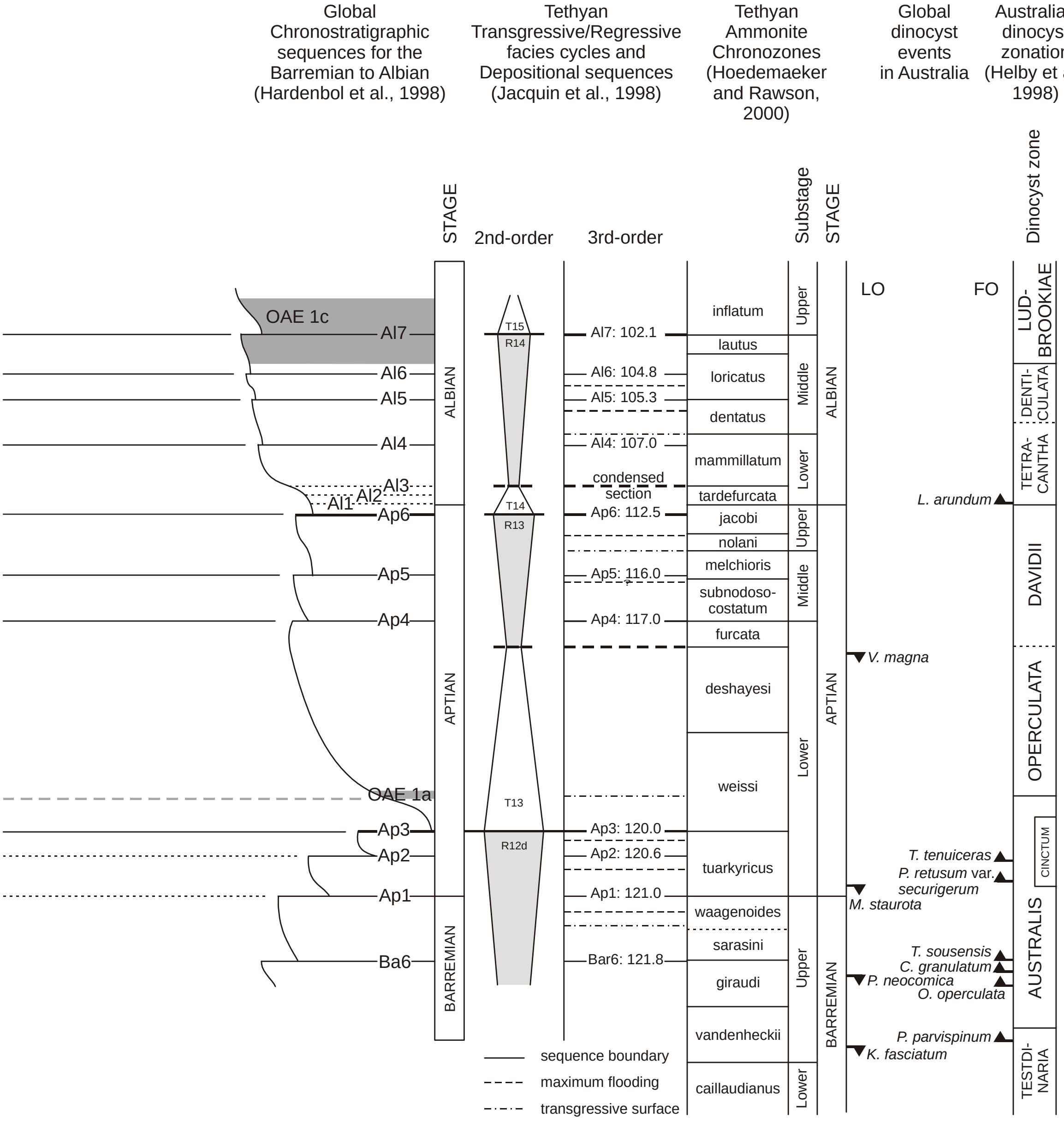

Figure 5 (continued).

the *M. tetracantha* Zone (Helby et al., 1987).

Segment C12

It falls within the Tehtyan *mammillatum* ammonite Zone (Lower-Middle Albian) and the Australian *M. tetracantha* dinocyst Zone. Besides the LO of *D. cerviculum* no further dinocyst events were observed.

Segment C13

This segment correlates to the Tethyan *dentatus* and *loricatus* ammonite zones (Middle Albian) and contains sequence boundary Al5 of Jacquin et al. (1998).

In Australian sections this sequence boundary correlates with the LO of *M. tetracantha* and marks the zonal boundary between the *M. tetracantha*-*C. denticulata* dinocyst zones.

Segment C14

It falls within the Tethyan *loricatus* and *lautus* ammonite zones (Upper Albian) and sequence boundary Al6 of Jacquin et al. (1998) lies in the lower part of this segment.

In the Austral Realm this segment contains the lower part of the organic rich Toolebuc Formation, inferred to be an equivalent of the black shales related with OAE 1c (Chapter 4). It further correlates to the Austral *E. ludbrookiae* Zone and the eponymous species shows a FO at the base of the dinocyst zone.

The top of this segment is defined by sequence boundary Al7, which also defines the Middle-Upper Albian Substage boundary and the transition between the regressive R14 and transgressive T15 cycles in Jacquin et al. (1998).

Segment C15

This segment corresponds to the Tethyan *inflatum* ammonite Zone (Upper Albian) and lies at the base of transgressive cycle T15 of Jacquin et al. (1998).

It correlates to the upper part of the Australian Toolebuc Formation and falls in the *E. ludbrookiae* Zone. Above the Toolebuc, within the *E. ludbrookiae* Zone, the FOs of *A. parvum* and *P. deflandrei* can occur.

5. Discussion

Previous attempts to correlate Lower Cretaceous sequences from Australia to a standard biostratigraphic scale have failed due to the endemic character, or even total lack of fossil groups (like ammonites, belemnites, foraminifera, or nannofossils, i.e. traditionally used to establish chronostratigraphic zonations) from the Australian sections. In recent years, however, organic-walled dinoflagellate cysts have been successfully applied to biostratigraphically correlate sequences from different realms (e.g. Prauss, 1993; Hoedemaeker and Leereveld, 1995; Wilpshaar, 1995; Leereveld, 1997; Hoedemaeker, 1999; Torricelli, 2000). In the present study fine-stratigraphic cross hemisphere correlation is established by means of a selection of diagnostic dinocyst events recognized in ammonite controlled Tethyan and Boreal sections (Chapters 2, 3, and 4). The combination of these palynological events with events in the $\delta^{13}C_{org}$ isotope records, tied to the chronostratigraphic standard for the Cretaceous (e.g. Hoedemaeker et al., 1993; Erba, 1996; Rawson, 1996; Hart et al., 1996; Hardenbol et al., 1998; Jaqcuin et al., 1998; Hoedemaeker and Rawson, 2000) enables firm correlation of Stage and Substage boundaries for the Cretaceous System in Australia. Additionally, evaluation of detailed quantitative data of palynological assemblages and $\delta^{13}C_{org}$ isotope composition permit recognition of eustatic sea-level variations as well as of palaeoenvironmental and palaeoclimatic changes in Australian basins (Oosting et al., in prep.; Chapters 2, 3, and 4).

Direct correlation of sections from the North West Shelf of Australia (DSDP site 263), Carpentaria Basin (BMR Mossman-1) and the Eromanga Basin (GSQ Hughenden-7, GSQ Eromanga-1 and GSQ Manuka-1) with Barremian-Albian ammonite calibrated Tethyan and Boreal successions revealed eleven dinocyst events useful for global biostratigraphic correlation (Oosting et al., in prep.; Chapters 2, 3 and 4). These events are: LO of *K. fasciatum*, FO of *P. parvispinum*, FO of *O. operculata*, LO of *P. neocomica*, FO of *C. granulatum*, FO of *T. sousensis*, LO of *M. staurota*, FO of *P. retusum* var. *securigerum*, FO of *T. tenuiceras*, LO of *V. magna*, and FO of *L. arundum*. These dinocyst events in Tethyan and Boreal sequences occur in the Barremian to Albian. This age assessment is confirmed by the recognition of isotope segments C2 to C15 (C1 was inferred tentatively in DSDP site 263; Chapter 3), being characteristic of the uppermost Barremian to

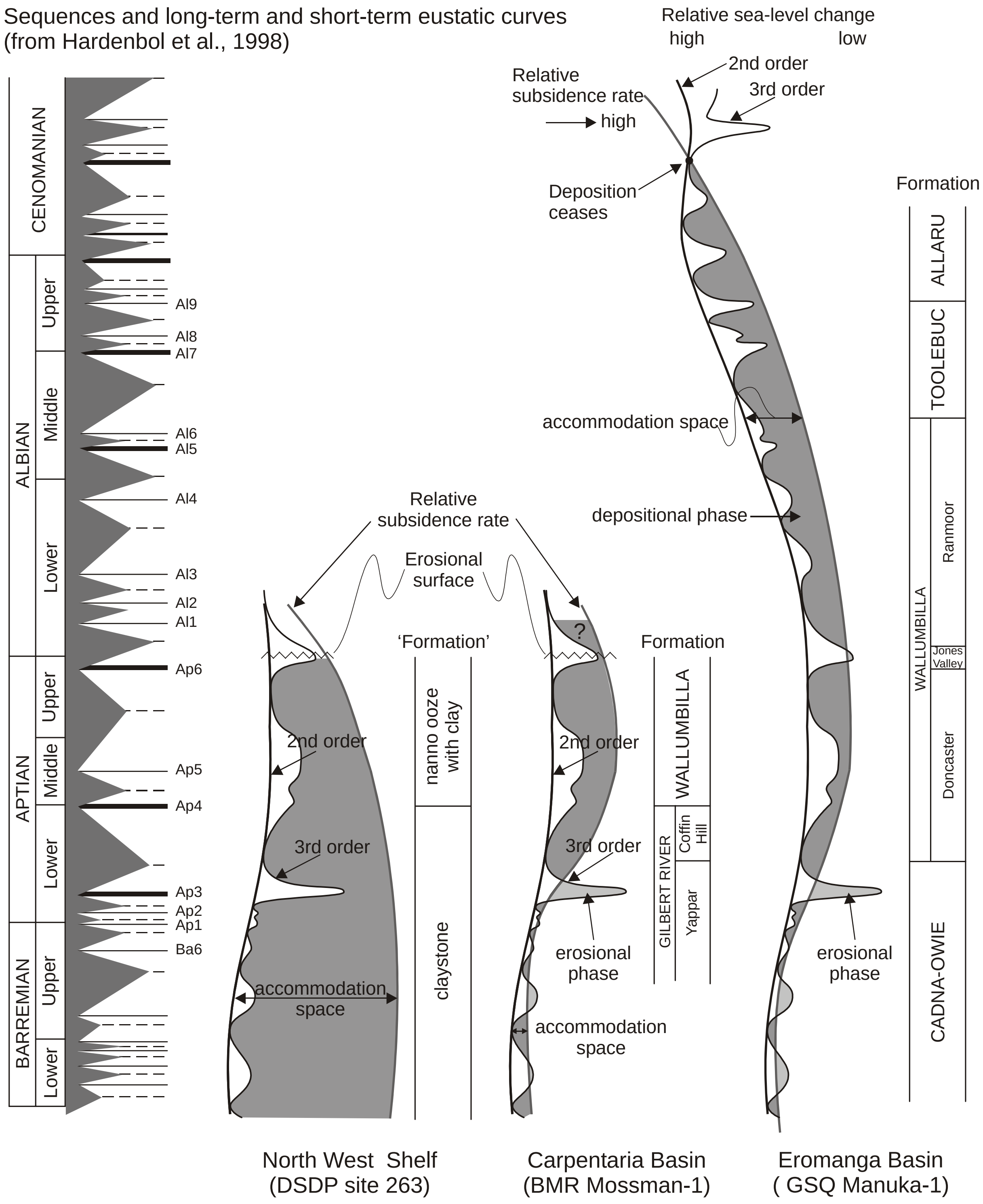

Figure 6. Relation for the North West Shelf, the Carpentaria and Eromanga basins between: sequences, relative 2nd and 3rd order eustatic changes (based on Hardenbol et al., 1998), relative subsidence, and generalized lithology for the basins.

Upper Albian (see in Menegatti et al., 1998; Bralower et al., 1999). With the stratigraphical interval defined, the reconstructed sea-level fluctuations, based on distribution patterns within the palynological assemblages, for the studied sections were compared to the eustatic sea-level curve of Hardenbol et al. (1998) and Jacquin et al. (1998), allowing identification of the 2nd order and most of the 3rd order fluctuations. The 3rd order cycles inferred for the sequences in this study with stratigraphic control comprise the sequence boundaries (SB): Ba6, Ap3-Ap6, Al4-Al7; and SBs tentatively inferred: Ap1, Ap2, Al1-Al3 (Figure 5). Most sequence boundaries either correspond or approximate Stage or Substage boundaries, e.g. Ba6-Al1 (transition from Barremian to Aptian), Ap4-Ap5 (Early to Middle Aptian), Ap6-Al1 (Aptian to Albian), Al4-Al5 (Early to Middle Aptian), Al7 (Middle-Upper Albian Substage boundary). Below, the deduced Stage and Substage boundaries for the Late Barremian to the Upper Albian are discussed and evaluated.

5.1 *Late Barremian*

During the Late Barremian the global, 2nd order sea-level fall superimposed on a 3rd order fall of regressive cycle R12 occurred (Hardenbol et al., 1998; Jaquin et al., 1998). The end of the 3rd order cycle is marked by SB Ba6, at the top of the *giraudi* ammonite Chronozone (Jacquin et al., 1998); prior to the FO of *T. sousensis* in the *sarasini* ammonite Chronozone (see Chapter 3). Such a sea-level regime would generally inhibit connections between basins or oceans. However, according to Exon and Buffler (1992) the north-western margin of Australia started to thermally subside in the Valanginian-Hauterivian, which continued into the Barremian. This gradual deepening eventually led to deposition of hemipelagic clays (e.g. DSDP site 263; Chapter 2). Furthermore, based on micro-palaeontological studies (e.g. nannofossils and foraminifera) Baumgartner et al. (1992) inferred that the north-western Australian margin was affected by relatively cool waters for this time interval. This agrees with the present study, in this interval dinocysts associated with cool-temperate water conditions (e.g. species of *Aprobolocysta*, *C. granulatum*, *D. nanna* and *V. magna*, see Chapter 3) occur abudantly. The dinocyst assemblages also indicate a progressive shift towards more open marine conditions over this time interval. The inferred cooler water conditions at the western Australian margin, compared to those in the western Mediterranean Tethys, imply that a circumfluent current system existed around the Antarctic-Australian landmass (Figure 6).

Another characteristic of the dinocyst assemblages from North Western Australia is the common occurrence of typical Austral dinocysts (e.g., *K. scruttilinum*, *E. vinckensis* and *H. postprojecta*), taxa that to date only have been reported from Australia. However, the occurrence of global dinocyst events (e.g., LO *K. fasciatum*, FOs *P. parvispinum* and *O. operculata*) indicates that a connection between the Tethyan and Austral Realm must have existed to some degree in order for these taxa to simultaneously first occur in the different realms. Mean while in the Late Barremian of the north-eastern Australian Carpentaria Basin shallow marine conditions undergoing strong fluviatile influence prevailed, resulting in the deposition of the Yappar Member of the Gilbert River Formation, while in the central Australian Eromanga Basin dominantly fluviatile conditions prevailed with deposition of the Cadna-owie Formation (Figure 7).

5.2 *Aptian*

Early Aptian, including OAE 1a

In the dinocyst assemblages the Barremian-Aptian transition interval is most clearly indicated in the dinocyst assemblages by the FO of *T. tenuiceras*. This taxon is present in all the Australian sedimentary basins studied herein and as such indicates to be a potential marker for earliest Aptian deposits on a regional as well as on a global scale (this study, Chapters 2, 3 and 4; Oosting et al., in prep.; Erba et al., 1996). The FO of *T. tenuiceras* lies prior to major sequence boundary Ap3, which marks the abrupt ending of regressive sea-level cycle R12d in the earliest Aptian (Jacquin et al., 1998). The return to relatively high sea level immediately after this level (onset of transgression cycle T13 of Jacquin et al., 1998) is generally believed to result of global warming due to intense volcanic CO_2 outgassing during construction of the Ontong Java Plateau and Nova Canton Trough (e.g., Larson, 1991; Larson and Erba, 1999), which resulted in the strong negative excursion of isotope segment C3. Although, in the Australian sequences C3 is of smaller magnitude than observed in sections from other regions (e.g., Menegatti et al., 1998; Bralower et al., 1999; Jenkyns and Wilson, 1999; Jahren et al., 2001; Price, 2003), the overall characteristics in the organic-carbon-isotope records are the same (Figure 4 and 5; this study, Chapter 3 Figure 6). Potentially segment C3 is contained in the Australian sequences but because of the very narrow time interval in which it occurs, combined with the low sample resolution used, the actual excursion related with C3 was probably not detected. The following strong positive shift in global $\delta^{13}C_{org}$ values of segments C4 to C6, related to OAE 1a, correlate to the transgressive systems tract of cycle Ap3 (this study, Chapter 3, Figure 8; Hardenbol et al., 1998); in Australia this level corresponds with the dinocyst zonal boundary between the *M. australis* and *O. operculata* zones.

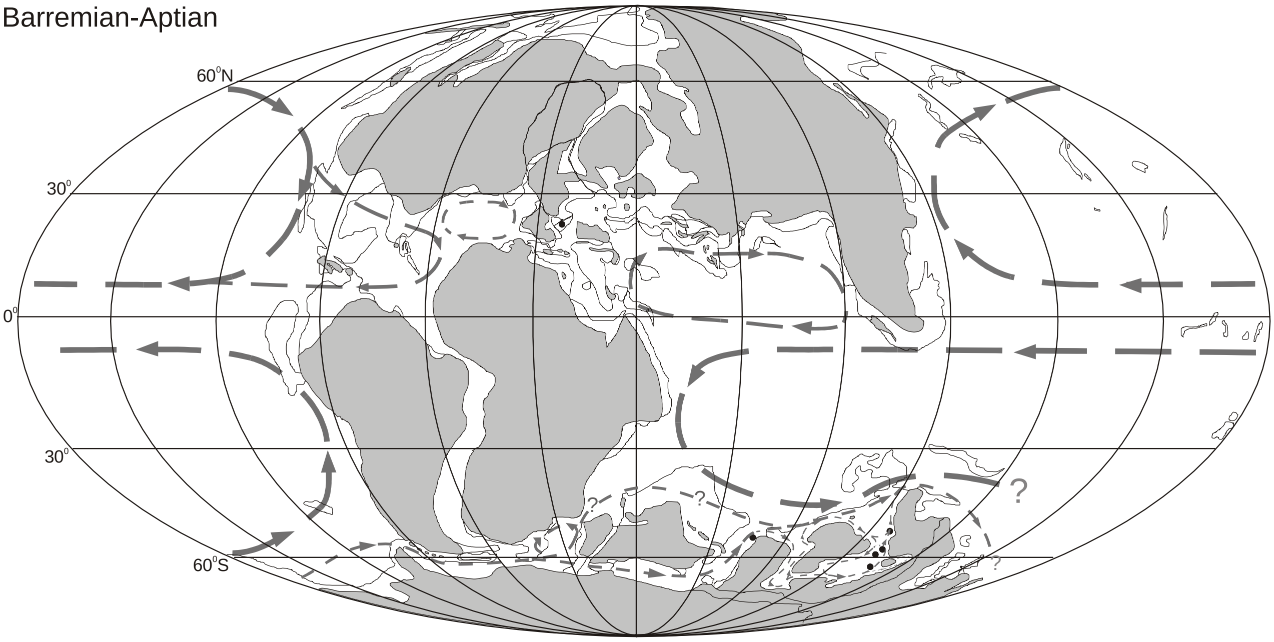

Figure 7. Map for the Barremian-Aptian with circumfluent current system around the Antarctic-Australian landmass.

In the Tethyan Realm, OAE 1a is suggested to relate to humid conditions and increased runoff rates due to enhancement of the hydrological cycle (Menegatti et al., 1998), while in Australia the dinocyst assemblages and vegetational reconstructions indicate cooler and drier conditions (Chapter 3). Apparently global warming caused humid conditions to increase exponentially around the equator as cooler and drier circumstances ruled at higher southern latitudes. Furthermore, an increase in relative sea level could have led to intensification of the already existing circumfluent current around the Antarctic-Australian landmass and consequently, to thermal isolation of this continent. The presence of cooler, and therefore better oxygenated, waters could also explain why proper black shales did not develop in Australia, although primary productivity had increased, as is show by the minor peaks in *P. cretaceum* in the Carpentaria and Eromanga basins at the time of OAE 1a. This peak in primary productivity most likely relates to leaching of nutrients from the newly inundated land along the Australian continent related to the rapid transgression of the Ap3 cycle.

Middle Aptian

The Middle Aptian is characterized by relatively constant 2nd order and minor 3rd order sea-level variations (Hardenbol et al., 1998). In Australia this time corresponds with a change in depositional regime; from the onset of SB Ap4 calcareous rich sediments are deposited, i.e., at the North West Shelf deposition changes from clay to nanno fossil ooze, in the Carpentaria Basin from the marine sand deposits of the Coffin Hill to the first calcareous limestones at the base of the Wallumbilla Formation, and in the Eromanga Basin the Wallumbilla Formation contains intercalations of limestone. This depositional regime lasted throughout the Middle and Late Aptian and ended with SB Ap6 (Figure 6). The time of increased calcareous deposits coincides with a period of waters becoming less cool and an extension of warmer favouring vegetation types on the adjacent land (this study, Chapters 2, 3 and 4). This could point to a less intense circum Antarctic-Australian current due to which climatic and environmental conditions became more equable.

Late Aptian

For the position of the Middle-Late Aptian boundary only an approximation can be made, i.e. it lies between Ap5 and Ap6 (Hardenbol et al., 1998; Jacquin et al., 1998), which correlates to the middle *D. davidii* dinocyst Zone in Australia but further diagnostic dinocyst events do not occur.

The Late Aptian ends with a sharp 3rd order sea-level fall inferred to correspond to SB Ap6 (Figure 6).

5.3 *Albian*

Early Albian

The base of the Early Albian can be put immediately after sequence boundary Ap6 (Hardenbol et al., 1998; Jacquin et al., 1998), which in Australia is generally marked by a sandy or sandstone interval (e.g., the Jones Valley Member in the Eromanga and Carpentaria Basins, Figure 11). This level in the global $\delta^{13}C_{org}$ isotope records corresponds to the base of segment C11.

In global correlations based on dinocysts, the best approximation for the Aptian-Albian boundary is the FO of *L. arundum* (Leereveld, 1995; Hart et al, 1996; this study, Chapter 4). In Australia the FO of *L. arundum* generally lies above the sandstone unit associated with Ap6.

From the onset of the Albian, immediately after Ap6, a 2nd order sea-level rise occurs (Hardenbol et al., 1998; Jacquin et al., 1998). According to Jacquin et al. (1998) the first three Albian, short-term 3rd order cycles Al1-Al3 are contained in a condensed section in pelagic sequences and are therefore hard to detect. In the present study these three SBs are though to fall within the sandstone unit (Jones Valley Member) at the base of the *M. tetracantha* Zone and most likely indicates a hiatus, which extent is hard to approximate. However, inferring the following SB as Al4 is based on the start of an increase in oceanic dinocysts in the Eromanga Basin and the inception of planktic foraminifera (reported by Campbell and Haig, 1999), apparently waterdepth had risen to such a degree that conditions became favourable for these groups. In agreement with Hardenbol et al. (1987), sea-level from the onset of the Albian starts to reach higher levels between the Al3 to Al4 cycle.

Middle Albian

During the Middle Albian global sea-level continued to rise (Hardenbol et al., 1998). Based on changes in lithology reported by Balfe (1978, 1979) and Almond (1983), on the distribution patterns of the palynological assemblages observed in this study, and on changes in the foraminiferal composition as reported by Campbell and Haig (1999), the Middle Albian SB Al5 and Al6 (Hardenbol et al., 1998; Jacquin et al., 1998) were inferred. These SBs lie within an interval which reflects a deepening depositional environment from the base toward the top of the Middle Albian e.g. overall, the amount of oceanic dinocysts increases coeval with an increase of mudstones relative to sandstones. However, because of lack of other diagnostic events (e.g., dinocyst events or $\delta^{13}C_{org}$ isotope segments), the extent of this Substage can not be determined for the Australian sequences (Figure 5).

Late Albian, including OAE 1c

The Middle-Late Albian is defined by sequence boundary Al7 (Hardenbol et al., 1998; Jacquin et al., 1998; this study, Chapter 4) and the transition between isotope segments C14 and C15 (this study, Chapter 4; see also Bralower et al., 1999). Both these phenomena were observed within the Australian organic rich sediments of the Toolebuc Formation (Figure 5), which correlates to the *A. albianus* NC 9B nannofossil zone (e.g. Bralower et al. 1993) and the *H. infracretacea* foraminiferal zone (Haig, 1979; Campbell and Haig, 1999). In the dinocyst records no global events were observed for this time interval; in Australian records the Toolebuc correlates to the *E. ludbrookiae* dinocyst Zone of Helby et al. (1987). However, the inferred isotope segments C14 and C15, combined with sequence boundary Al7, clearly shows that the Toolebuc Formation correlates to OAE 1c.

This study further indicates a threefold division in sea-level for the Toolebuc Fm, e.g. firstly; a sea-level rise in the lower Toolebuc Fm caused leaching of nutrients and consequent high primary productivity; secondly, in the middle Toolebuc a sea level fall caused influx of terrestrial organic matter and further increase in productivity; and thirdly, in the later part a next sea-level rise associated with increased $CaCO_3$ production and high but decreasing productivity. These distinct variations in sea-level could explain why the Toolebuc in marginal settings is exclusively coeval with the younger part in more distal sections (as stated by Moore et al, 1986), i.e., during the middle, regressive, Toolebuc earlier shallow marine deposits were transported to deeper parts of the basin, while during the next transgressive phase of the upper Toolebuc Fm the formed organic matter along the new margin could be preserved as well.

The preservation of organic matter indicates that dysoxic or anoxic conditions must have existed at the sediment-water interface, however, the presence of microplankton (e.g., dinocysts, nannofossils, foraminifera and radiolaria), ammonites, belemnites, and fish remains throughout the Toolebuc Fm indicates that at least the upper parts of the water column were in general relatively well oxygenated.

In agreement with the climatic changes inferred for the Early Cretaceous, the succession of events in the Toolebuc Fm shows a fluctuating pattern toward increasingly warmer environmental conditions.

Conclusions

Dinoflagellate cyst biostratigraphy can be applied for direct correlation of Barremian-Albian Australian sequences with European ammonite controlled standard successions like at Angles (SE France).

The study on sections from the NW Shelf of Australia (DSDP site 263), the Carpentaria Basin (BMR Mossman-1), and the Eromanga Basin (GSQ Hughenden-7, GSQ Eromanga-1 and GSQ Manuka-1) provides a composite of eleven successive dinocyst events which can be used for global correlations. These events are: LO of *K. fasciatum* and FO of *P. parvispinum*, FO of *O. operculata*, LO of *P. neocomica*, FO of *C. granulatum*, FO of *T. sousensis*, LO of *M. staurota*, FO of *P. retusum* var. *securigerum*, FO of *T. tenuiceras*, LO of *V. magna*, and FO of *L. arundum*. Comparison with the Australian zonal scheme by Helby et al. (1987) reveals seven Barremian to Albian dinocyst zones, e.g. the *M. testudinaria* Zone, *M. australis* Zone, *O. operculata* Zone, *D. davidii* Zone, *M. tetracantha* Zone, *C. denticulata* Zone and *E. ludbrookiae* Zone. Due to the strongly facies dependance of the *O. cinctum* (was *A. cinctum*) Zone it was not distinguished as a seperate zone but incorporated within the upper *M. australis* Zone.

Based on the global dinocyst events the investigated intervals correlate to the Barremian-Albian. This is confirmed by the synchroneity of the inferred sea-level signature for the study areas and the eustatic sea-level curve by Hardenbol et al. (1998) and Jacquin et al. (1998) of which 2nd and 3rd order eustatic cycles for the Upper Barremian to Late Albian could be identified (Ba6 to Al7). Additionally, the global isotope segments C1 to C15 for the Upper Barremian to Late Albian as defined by Menegatti et al. (1998) and Bralower et al. (1999) could be identified.

The combination of bio and chemostratigraphy and the inferred sea-level fluctuations enabled verification and refinement of positions for the Australian, Early Cretaceous Stage and Substage boundaries within the Australian Mesozoic dinoflagellate cyst zonation of Helby et al. (1987).

- The base of the Upper Barremian, within the Austral *M. testudinaria* Zone.

Is inferred to reflect the situation in NW Europe where the Substage boundary lies between the LO of *K. fasciatum* and the FO of *P. parvispinum*.

- The Barremian-Aptian boundary, within the uppermost *M. australis* Zone.

When present in the Australian sequences, the FO of *P. retusum* var. *securigerum* (lower *tuarkyricus* ammonite Chronozone) approximates the Stage boundary best. However, due to its rare presence, the FO of *T. tenuiceras* (occurs in almost all Barremain-Aptian intervals from Australia) seems a better approximate (*tuarkyricus* ammonite Chronozone; in between SB Ap2 and Ap3; within isotope segment C2; uppermost *M. australis* Zone).

- The Lower-Middle Aptian boundary, within the lowermost *D. davidii* Zone.

Lies in between SB Ap4 and Ap5, corresponds to a level within the upper isotope segment C8 or lower C9.

- The Middle-Upper Aptian boundary, within the middle *D. davidii* Zone.

Approximates a level between Ap5 and Ap6; further diagnostic events were not inferred.

- The Aptian-Albian boundary corresponds with the base of the *D. davidii* Zone.

Based on dinocysts it is best approximated by the FO of *L. arundum* (*tardefurcata* ammonite Zone), in the Eromanga and Carpentaria basins this taxon incepts immediately above the Jones Valley Member (which contains Al1, Al2 and/or Al3; a possible hiatus is inferred for this interval); lies immediately above SB Ap6 and at the base of isotope segment C11.

- The Lower-Middle Albian boundary within the *M. tetracantha* Zone.

For this Substage boundary no diagnostic events could be inferred. Closest approximation is that it lies in between SB Al 4 and Al5, and within isotope segment C12.

- The Middle-Upper Albian boundary lies within the *E. ludbrookiae* Zone.

Correlates to a sharp sea-level fall corresponding to SB Al7 within the Toolebuc Formation.

Barremian-Aptian palynological distribution patterns for the three Australian study areas indicate cool-temperate waters during the Late Barremian to earliest Aptian. The progressive development from open marine neritic to hemipelagic depositional environments probably was in response to thermal subsidence of the Cuvier Abyssal Plain after the marginal collapse of the Cape Range Fracture Zone area in the Valanginian-Hauterivian (Exon and Buffler, 1992). This interval is further characterized by high amounts of cool-temperate dinocysts which are paralleled by increased $\delta^{13}C_{org}$ values. The FO of *C. granulatum* is possibly related to these cooler conditions, instead of occurring in the uppermost Barremian, it shows a delayed first occurrence in the Lower Aptian. This change to cool water conditions, whcih is coeval with the rapid sea-level rise of the Ap3 sequence, supports the view advanced by Baumgartner et al. (1992) that a circum-Antarctic-Australian current system affected the western Australian margin during the Barremian-Aptian.

Within the earliest Aptian from the Carpentaria Basin (BMR Mossman-1) global carbon isotope segments C4-C6 correspond with the transgressive systems tract of the Ap3 sequence, during which a probable equivalent of the black shale related to OAE 1a was deposited. Although, this unit is associated with an increase in productivity and significant environmental changes associated with an OAE event do occur, the interval does not show elevated TOC values.

The Toolebuc Formation is inferred to be equivalent to OAE 1c. It correlates to an interval around the Middle-Late Albian Substage boundary, contains organic-carbon-isotope segments C14 and C15 and represent a 3rd order sea-level rise, short-term fall (inferred to mark sequence boundary Al7) and consecutive rise again. This unit is associated with an increase in productivity, significant environmental change (relatively more cool-temperate and dry conditions during segment C14 in comparison with segment C15, when conditions become more warm and humid), and shows elevated TOC and carbonate levels.